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(54) Silicon Aluminum Oxynitride Based Article with Improved Fracture Toughness and Strength

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SILICON ALUMINUM OXYNITRIDE BASED ARTICLE  
WITH IMPROVED FRACTURE TOUGHNESS AND STRENGTH

This application contains subject matter related to matter disclosed and claimed in commonly assigned co-pending Canadian Patent Application No. 591,219-9, filed concurrently herewith.

10        This invention relates to fracture and abrasion resistant materials and to articles of manufacture made therefrom. More particularly, it is concerned with silicon aluminum oxynitride-based ceramic bodies exhibiting both improved fracture toughness and improved strength.

20        The need for structural materials for cutting tool applications, with improved toughness and improved strength at room and elevated temperatures, and with chemical inertness, has generated a widespread interest in ceramic materials as candidates to fulfill these requirements. Conventional ceramic cutting tool materials have failed to find wide application, primarily due to their low fracture toughness.

      Therefore, many materials have been evaluated to improve ceramic performance, such as silicon aluminum oxynitride-based monolithic and composite materials for cutting tool applications.

30        Silicon aluminum oxynitride-based ceramics have also been considered for use as structural components for advanced turbine engines. A critical factor which limits the widespread application of these materials in such heat engines is their tendency to catastrophic failure. Accordingly, improvement in strength and fracture toughness of these materials would improve their performance in the demanding heat engine environment, contributing to

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a more rapid development of these high performance turbine engines.

Many improvements have been made in the toughness, abrasion resistance, high temperature strength and chemical inertness, but the stringent conditions encountered by heat engine components and cutting tools demand even further improvement in material characteristics. In many applications, for example in gray cast iron machining, silicon aluminum oxynitride tool wear has been found

10 to be dominated by abrasion. Even at cutting speeds as high as 5000 sfm, chemical reactions between tool and workpiece are negligible in comparison. It has been found that abrasion resistance for silicon aluminum oxynitride ceramic cutting tool materials is directly proportional to  $K_{IC}^{3/4} H^{1/2}$ , where  $K_{IC}$  is the fracture toughness and H is the hardness. Therefore, it is anticipated that further improvement in the fracture toughness of silicon aluminum oxynitride-based ceramic materials could bring about significant increases in both

20 reliability and abrasive wear resistance, providing materials for cutting tools with new and improved characteristics.

Attempts have been made to increase the fracture toughness of silicon aluminum oxynitride materials through the development of a composite, in which dispersed particulate, fiber, or whisker materials are included in a silicon aluminum oxynitride-based matrix. The added complexity of composites, however, can result in improvements in fracture toughness at the expense of

30 strength. The present invention provides new and improved monolithic and composite silicon-aluminum oxynitride-based ceramic materials exhibiting both improved fracture toughness and improved strength.

The wear-resistant silicon aluminum oxynitride-based bodies of the invention are also useful in other wear

1336101

88-3-428 CN

-3-

part and structural applications, for example in dies, nozzles, etc.

According to one aspect of the invention, there is provided a densified silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising: a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5; and an intergranular, bonding, silica-based second phase comprising silica and one or more suitable oxide densification aids; wherein the ceramic body is formed from a starting formulation comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of the one or more densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component; and the ceramic body has a fracture toughness of at least  $5.0 \text{ MPa}\cdot\text{m}^{1/2}$  and a modulus of rupture of at least 700 MPa.

The ceramic body according to the invention optionally further includes refractory whiskers or fibers having an aspect ratio of about 3-150, uniformly distributed in the ceramic body. The equivalent diameter of the whiskers or fibers is greater than that of the silicon aluminum oxynitride grains. The starting formulation comprises the silicon aluminum oxynitride component, the one or more densification aids, and about 10-50% by volume refractory whiskers or fibers, based on the total volume of the ceramic body.

In accordance with another aspect of the invention, there is provided a process for producing a densified silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising the step of: densifying a blended powder mixture comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of one or more suitable oxide densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component, in a nitrogen or inert atmosphere at about 1650-1850°C and about 3-30,000 psi, for a time sufficient to produce a ceramic body comprising: a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5; and an intergranular, bonding, silica-based second phase comprising silica and the one or more densification aids; and having a fracture toughness of at least 5.0 MPa·m<sup>1/2</sup> and a strength of at least 700 MPa.

In the process according to the invention, the blended powder mixture densified in the densifying step optionally further includes about 10-50% by volume of refractory whiskers or fibers having an aspect ratio of about 3-150, based on the total volume of the ceramic body. The equivalent diameters of the whiskers or fibers and the silicon aluminum oxynitride component in the starting formulation, and the densification time are selected to produce the densified ceramic body in which the equivalent diameter of the whiskers or fibers is

greater than that of the silicon aluminum oxynitride grains.

According to other aspects of the invention, there are provided methods according to the invention for continuous or interrupted machining of grey cast iron stock or nickel-based superalloy stock involve milling, turning, or boring the stock with a cutting tool comprising a densified silicon aluminum oxynitride-based ceramic body having a fracture toughness of at least 5.0 MPa·m<sup>1/2</sup> and a modulus of rupture of at least 700 MPa. The ceramic body includes a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, and an intergranular, bonding, silica-based second phase comprising silica and one or more suitable oxide densification aids. In the first phase, if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5. The ceramic body is formed from a starting formulation comprising a silicon aluminum oxynitride component selected from prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of the one or more densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component. The machining speed for the grey cast iron stock is about 800-6000 sfm, and the feed rate is about 0.01-0.04 in/rev. The machining speed for the nickel-based superalloy stock is about 200-1500 sfm and the feed rate is about 0.005-0.04 in/rev.

For a better understanding of the present invention, together with other and further objects, advantages and



capabilities thereof, reference is made to the following disclosure and claims.

The densified silicon aluminum oxynitride-based ceramic bodies of the present invention comprise silicon aluminum oxynitride grains bonded together by an intergranular phase of a silica-based material. The silica is normally present in the silicon nitride component of the starting formulation, or in the prereacted silicon aluminum oxynitride. The silica content of the intergranular phase may be controlled in known manner by the addition of aluminum nitride to the starting formulation.

The oxide densification aids are also present in the intergranular phase. The preferred densification aid is yttria, included in the starting formulation in an amount of about 2-8% by weight based on the combined weight of the silicon aluminum oxynitride and the densification aids. The yttria may be used alone or in combination with other suitable densification aids, present in the starting formulation in an amount of about 0.5-12% by weight. Optionally, the other suitable oxide densification aids may be included in the starting formulation without the yttria. The densification aid, or combination of densification aids is selected to optimize properties desired in the ceramic body, for example high temperature strength, chemical resistance, or fracture toughness. Such other suitable oxide densification aids include, but are not limited to magnesia, ceria, zirconia, and hafnia. The total amount of densification aids included in the starting formulation preferably should not exceed 12% by weight.

Impurities may be present in the starting materials used for the manufacture of the ceramic body. The impurities tend to become concentrated in the intergranular phase during preparation of the ceramic body. Therefore high purity starting materials are desired, preferably those having less than about 0.1% by weight

cation impurities. A typical undesirable impurity is calcium, which tends to deleteriously affect the second phase and the high temperature properties.

The monolithic ceramic bodies described above have a microstructure of silicon aluminum oxynitride grains bonded together by a continuous, bonding, intergranular second phase formed from the densifying additive. Because the intergranular second phase is continuous, its characteristics profoundly affect the high temperature properties of the monolithic ceramic material. The monolithic ceramic bodies of the present invention possess high fracture toughness and high strength at temperatures in excess of 1200°C, preferably in excess of 1500°C.

In another aspect of the present invention whiskers or fibers of hard refractory silicon carbide or a transition metal carbide, nitride, or carbonitride, or mixtures or solid solutions thereof are dispersed in a two-phase matrix. By the term transition metal carbide, nitride, or carbonitride, as used throughout this specification and claims, is meant any carbide, nitride, or carbonitride of titanium, hafnium, tantalum, niobium, or tungsten.

The hard refractory whiskers incorporated into materials in accordance with this invention each comprise a single crystal, while the fibers are polycrystalline. The whiskers or fibers preferably have an average diameter of about 1-5 microns and an average length of about 10-250 microns, with a preferred aspect ratio of length to diameter of about 3-150.

These dispersoids may be coated if desired with a different hard refractory material deposited as one or more polycrystalline layers on the fiber or whisker. Suitable coatings for the silicon carbide whiskers or fibers include refractory oxides and nitrides. Those for the metal carbide, nitride, or carbonitride dispersoids

include refractory oxides, nitrides, or carbides. Such coated dispersoids may be selected to optimize bulk (e.g. mechanical) properties and surface (e.g. chemical) properties of the dispersoid materials in the matrix.

The useful life and performance of composite bodies in accordance with this aspect of the invention depend, in large part, on the volume taken up by the dispersed phase in the article. The whiskers or fibers should comprise about 10-50% by volume of the densified composite.

10 In accordance with the principles of the present invention, the hard refractory dispersoids are uniformly distributed in a two-phase matrix. The first phase of the matrix consists essentially of grains of silicon aluminum oxynitride, as described above for the monolithic ceramic body not including the whiskers or fibers. The intergranular phase or second phase of the matrix is formed from one or more densification aids, as also described above. The degree of purity of the materials  
20 used in the starting formulation for the composite ceramic bodies of the invention is as described above for the monolithic bodies.

The composite ceramic bodies described herein have a composite microstructure of refractory whiskers or fibers uniformly dispersed in a matrix containing a first phase of silicon aluminum oxynitride grains and a continuous, bonding, intergranular second phase formed from the densifying additive. Because the intergranular phase is continuous, its characteristics profoundly affect the  
30 high temperature properties of the composite material. The composite ceramic bodies of the present invention possess high fracture toughness and high strength at temperatures in excess of 1200°C, preferably in excess of 1500°C.

Ceramic bodies formed from the densified monolithic or composite materials according to the present invention

1336101

- 9 -

may be coated with one or more adherent layers of hard refractory materials, for example by known chemical vapor deposition or physical vapor deposition techniques. The hard refractory materials suitable for coating monolithic or composite ceramic bodies according to the present invention include the refractory carbides, nitrides, and carbonitrides of titanium, zirconium, hafnium, vanadium, niobium, tantalum, chromium, molybdenum, and tungsten, and mixtures and solid solutions thereof, and alumina, zirconia, and hafnia, and mixtures and solid solutions thereof. Each layer may be the same or different from adjacent or other layers. Such coatings are especially advantageous when applied to cutting tools formed from the densified composites of the present invention.

In accordance with yet another aspect of the invention, a process is provided for preparing the monolithic or composite bodies described above, densifying the materials to densities approaching theoretical density, i.e. greater than 98% of theoretical, while achieving optimum levels of mechanical strength and toughness at both room temperature and elevated temperature, making the bodies particularly useful as cutting tools in metal removing applications, or as structural components for turbine engines.

The silicon aluminum oxynitride component, the densification aid, and optionally the hard refractory whiskers or fibers are blended to form a starting formulation or powder mixture. The powder mixture is then densified or compacted to a high density, for example by sintering, hot pressing, or hot isostatic pressing techniques.

A starting composition for the production of the strong, tough, abrasion resistant materials according to the present invention may be made by employing powdered starting materials, i.e. silicon nitride and alumina, to form the first phase grains. The powders are preferably of average particle size below about 3 microns. Alternatively, a prereacted silicon aluminum oxynitride powder may be employed.

- 10 Preferably, the silicon nitride and alumina powders are added in sufficient quantities to be equivalent to about 99-65% by volume silicon nitride and about 1-35% by volume alumina, of the total volume of the first and second phase powdered starting materials. The prereacted component preferably contains similar proportions of silicon nitride and alumina.

- 20 Densification of the silicon aluminum oxynitride-based monolithic material or the silicon aluminum oxynitride/whisker composite material is aided by the incorporation of one or more of the above-described densification aids into the initial powdered starting materials, or, as described in Patent 4,421,528, the densification aid may be incorporated into the prereacted powder.

- 30 In the starting formulations employed in the fabrication, hard refractory whiskers or fibers optionally comprise about 10-50% of the total volume of the densified article, as described above, while the densification aid comprises about 0.5-12% by weight, based on the combined weight of the densification aid and the silicon aluminum oxynitride component in the starting composition. In the starting formulation, the balance of the mixture normally comprises the silicon nitride and alumina powders or the prereacted silicon aluminum oxynitride powder.

The starting materials may be processed to a powder compact of adequate green strength by thoroughly mixing the matrix starting materials by processes such as dry milling or ball milling in a nonreactive liquid medium, such as toluene or methanol; admixing the whiskers or fibers, if included, by blending, preferably in a non-reactive liquid medium; and forming the mixture, for example by pressing, injection molding, extruding, or slip casting. Processing may also optionally include a  
10 presintering or prereacting step in which either the uncompact materials or the compact is heated at moderate temperatures.

Since the strength of monolithic or composite articles in accordance with this invention decreases with increasing porosity in the total compact, it is important that the compact be densified to a density as nearly approaching 100% of theoretical density as possible, preferably greater than 98% of theoretical density. The measure of percent of theoretical density is obtained by  
20 a weighted average of the densities of the components of the compact.

The microstructural tailoring of the ceramic materials described herein is critical to providing monolithic and composite bodies exhibiting both improved fracture toughness and improved strength. This microstructural tailoring involves careful control of the silicon aluminum oxynitride grain size and aspect ratio. In the composite materials it also involves careful control of the dispersoid content and its size relative  
30 to the matrix grains. These sizes are expressed as the equivalent diameters of the silicon aluminum oxynitride grains and the whiskers or fibers. By the term "equivalent diameter", as used throughout this specification and claims, is meant the average diameter of an equiaxed particle of the same volume as the particle, grain, whisker, or fiber. The terms "equivalent diameters",

1336101

88-3-428 CN

-12-

"grain size", "aspect ratio", and the like, as used throughout this specification and claims, refer to the average values of these measurements within the ceramic body.

10 An increase in both fracture toughness and strength of silicon aluminum oxynitride monolithic and composite materials with an increase in grain size is unexpected, since ceramics in general are expected to exhibit lower strength with increased grain size (Kingery, Introduction to Ceramics, John Wiley & Sons, Inc., NY, London 624 (1960); Evans, J. Am. Cer. Soc., 65, 127-137 (1982)). It has been further observed that silicon nitride ceramics containing alumina and yttria sintering aids exhibit this behavior (G. Watting et al., Sci. of Ceramics, Proc. Non Oxide Tech. and Eng. Ceramics, Limerick, Ireland (1986)).

20 It has been found, however, that an increase in grain size and control of the aspect ratio of the silicon aluminum oxynitride, through the densification process according to the invention, can achieve an increase in fracture toughness with an unexpected concomitant increase in the strength of the silicon aluminum oxynitride body.

30 Further, when reinforcing whiskers or fibers are included in the material, the whiskers or fibers being of a prescribed aspect ratio and relative size, a further increase in resistance to fracture may be achieved, again with a concomitant increase in strength. This too is unexpected in light of the teachings of U.S. Patent No. 4,543,345, which states that additions of silicon carbide whiskers to silicon nitride bodies do not produce increased toughness.

To achieve a monolithic or composite ceramic body according to the invention, the powder mixture described above is compacted and densified in nitrogen or an inert atmosphere, e.g. argon, at a pressure of about 3-30,000 psi and a temperature of about 1650-1850°C, and held at

the maximum temperature for a prolonged time, normally about 2-12 hours. The time at maximum temperature is sufficient to achieve grain growth in the silicon aluminum oxynitride component of the ceramic body and the microstructure described above. The improved properties of the resultant body are unexpected, in light of statements found in the prior art that extended times at high temperatures result in a decrease of fracture strength as well as fracture toughness (Zeigler, Heinrich, and  
10 Watting, J. Mater. Sci., 22, 3041-3086 (1987)).

The following Examples are presented to enable those skilled in the art to more clearly understand and practice the present invention. These Examples should not be considered as a limitation upon the scope of the present invention, but merely as being illustrative and representative thereof.

#### EXAMPLE 1

A powder mixture of 41.7% by weight silicon nitride,  
20 32.85% by weight alumina, and 4.02% by weight yttria is dry ball milled for 24 hours using silicon nitride milling media. The powder is processed in a graphite die coated with boron nitride, and is hot pressed at 3500 psi and 1725°C in nitrogen for 400 minutes. The ceramic bodies densified for 400 minutes show an increase in both fracture toughness and modulus of rupture (i.e. strength) at room and elevated temperature over bodies densified for shorter times. A turning operation is performed, using these ceramic bodies as cutting tools, on an  
30 Inconel workpiece (Inconel 718 (R<sub>C</sub>45)) at a cutting speed of 800 sfm and a feed rate of 0.006 in/rev. The depth of cut is 0.040 in. The bodies densified for 400 minutes show significantly less notch wear than those densified for shorter times. These improved properties result from the increase in the equivalent grain diameter of the



silicon aluminum oxynitride grains with the increase in hot pressing time.

EXAMPLE 2

A powder mixture of the composition described above for Example 1, but with 30% by volume of the powder mixture substituted by silicon carbide whiskers having an equivalent diameter of 1.95 microns and an aspect ratio of 6, is wet blended in methanol in a high shear blender to disperse the whiskers throughout the mixture. The blended mixture is then hot pressed as described above for Example 1 for 400 minutes. The resulting composite ceramic bodies exhibit improved properties and machining performance over the silicon aluminum oxynitride bodies of Examples 1.

The densified monolithic and composite ceramic bodies according to the invention are hard, non-porous, and exhibit room and elevated temperature strength and fracture toughness higher than that of conventional silicon aluminum oxynitride materials. These bodies are useful for ceramic articles including, but not limited to cutting tools, extrusion dies, nozzles, dies, bearings, and wear resistant structural parts. These articles are especially useful as ceramic components for heat engines and as shaped cutting tools for continuous or interrupted milling, turning, or boring of grey cast iron stock or high nickel (at least 50% nickel) alloy stock, e.g. Inconel.

While there has been shown and described what are at present considered the preferred embodiments of the invention, it will be apparent to those skilled in the art that various changes and modifications can be made therein without departing from the scope of the invention as defined by the claims.

THE EMBODIMENTS OF THE INVENTION FOR WHICH AN EXCLUSIVE  
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A densified silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising:

10 a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5; and

an intergranular, bonding, silica-based second phase comprising silica and one or more suitable oxide densification aids;

20 wherein the ceramic body is formed from a starting formulation comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of the one or more densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component; and

30 the ceramic body has a fracture toughness of at least  $5.0 \text{ MPa}\cdot\text{m}^{1/2}$  and a modulus of rupture of at least 700 MPa.

2. A ceramic body in accordance with claim 1 wherein the one or more other densification aids consist essentially of yttria, present in the starting formulation in an amount of about 2-8% by weight.

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3. A ceramic body in accordance with claim 1 wherein the silicon aluminum oxynitride grains have an equivalent diameter of about 0.25-3.5 microns, and an aspect ratio of about 1.5-10.

4. A coated silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising a ceramic body in accordance with claim 1 having deposited thereon an adherent, wear-resistant, refractory coating comprising one or more refractory layers.

5. A ceramic body in accordance with claim 1 further comprising refractory whiskers or fibers having an aspect ratio of about 3-150, uniformly distributed in the ceramic body;

wherein the equivalent diameter of the whiskers or fibers is greater than that of the silicon aluminum oxynitride grains; and

20 the starting formulation comprises the silicon aluminum oxynitride component, the one or more densification aids, and about 10-50% by volume refractory whiskers or fibers, based on the total volume of the ceramic body.

6. A ceramic body in accordance with claim 5 wherein the silicon aluminum oxynitride grains have an equivalent diameter of about 0.25-3.5 microns, and an aspect ratio of about 1.5-10.

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7. A ceramic body in accordance with claim 5 wherein the refractory whiskers or fibers are of materials selected from the group consisting of silicon carbide, silicon carbide coated with a refractory material, refractory metal carbides, refractory metal carbides coated with a refractory material, refractory metal

nitrides, and refractory metal nitrides coated with a refractory material.

8. A coated silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising a ceramic body in accordance with claim 5 having deposited thereon an adherent, wear-resistant, refractory coating comprising one or more refractory layers.

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9. A process for producing a densified silicon aluminum oxynitride-based ceramic body of improved fracture toughness and improved strength comprising the step of:

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densifying a blended powder mixture comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of one or more suitable oxide densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component, in a nitrogen or inert atmosphere at about 1650-1850°C and about 3-30,000 psi, for a time sufficient to produce a ceramic body comprising:

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a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5; and

an intergranular, bonding, silica-based second phase comprising silica and the one or more densification aids;

and having a fracture toughness of at least 5.0 MPa·m<sup>1/2</sup> and a strength of at least 700 MPa.

10. A process in accordance with claim 9 wherein the one or more densification aids consist essentially of yttria, the yttria being present in the powder mixture in an amount of about 2-8% by weight.

11. A process in accordance with claim 9 further  
10 comprising the step of depositing on the densified ceramic body an adherent, wear-resistant, refractory coating comprising one or more refractory layers.

12. A process in accordance with claim 9 wherein the silicon aluminum oxynitride grains in the densified ceramic body have an equivalent diameter of about 0.25-3.5 microns, and an aspect ratio of about 1.5-10.

13. A process in accordance with claim 9 wherein the  
20 blended powder mixture densified in the densifying step further comprises about 10-50% by volume of refractory whiskers or fibers having an aspect ratio of about 3-150, based on the total volume of the ceramic body; and the equivalent diameters of the whiskers or fibers and the silicon aluminum oxynitride component in the powder mixture, and the densification time are selected to produce the densified ceramic body in which the equivalent diameter of the whiskers or fibers is greater than that of the silicon aluminum oxynitride grains.

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14. A process in accordance with claim 13 wherein the refractory whiskers or fibers are of materials selected from the group consisting of silicon carbide, silicon carbide coated with a refractory material, refractory metal carbides, refractory metal carbides coated with a refractory material, refractory metal

nitrides, and refractory metal nitrides coated with a refractory material.

15. A process in accordance with claim 13 wherein the equivalent diameter of the whiskers or fibers in the densified ceramic body is about 0.3-10.0 microns, and the equivalent diameter of the silicon aluminum oxynitride grains is about 0.25-3.5 microns.

10 16. A process in accordance with claim 13 further comprising the step of depositing on the densified ceramic body an adherent, wear-resistant, refractory coating comprising one or more refractory layers.

17. A method for continuous or interrupted machining of grey cast iron stock comprising the step of milling, turning, or boring the stock with a cutting tool comprising a densified silicon aluminum oxynitride-based ceramic body having a fracture toughness of at least 5.0  
20 MPa·m<sup>1/2</sup> and a modulus of rupture of at least 700 MPa, the ceramic body comprising:

a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns the aspect ratio is at least about 1.5; and

30 an intergranular, bonding, silica-based second phase comprising silica and one or more suitable oxide densification aids;

wherein the ceramic body is formed from a starting formulation comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride

and silicon nitride plus alumina, and about 0.5-12% by weight of the one or more densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component;

wherein the machining speed is about 800-6000 sfm and the feed rate is about 0.01-0.04 in/rev.

18. A method for continuous or interrupted machining of nickel-based superalloy stock comprising the step of milling, turning, or boring the stock with a cutting tool comprising a densified silicon aluminum oxynitride-based ceramic body having a fracture toughness of at least 5.0 MPa·m<sup>1/2</sup> and a modulus of rupture of at least 700 MPa, the ceramic body comprising:

a first phase consisting essentially of silicon aluminum oxynitride grains having an aspect ratio of about 1-10 and an equivalent diameter of about 0.25-10 microns, wherein if the aspect ratio is less than about 1.5 the equivalent diameter is at least about 0.4 microns and if the equivalent diameter is less than about 0.4 microns, the aspect ratio is at least about 1.5; and

an intergranular, bonding, silica-based second phase comprising silica and one or more suitable oxide densification aids;

wherein the ceramic body is formed from a starting formulation comprising a silicon aluminum oxynitride component selected from the group consisting of prereacted silicon aluminum oxynitride and silicon nitride plus alumina, and about 0.5-12% by weight of the one or more densification aids, based on the combined weight of the one or more densification aids and the silicon aluminum oxynitride component;

1336101

88-3-428 CN

wherein the machining speed is about 200-1500 sfm and the  
feed rate is about 0.005-0.04 in/rev.

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